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Force Coefficients for Stranded and Smooth Cables

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Introduction

The shape of a cable when towed through water is determined by its weight and by the forces acting on it due to the water. For a given length these hydrodynamic forces are functions of towing speed, cable diameter, cable construction and angle to the direction of motion through the water.

Because dynamic forces on many rigid bodies have been found experimentally to be proportional to the square of speed, V, a force coefficient C is defined such that

$$\text{Force} = 1/2 \ \rho \ V^2 \ A \ C$$

where ρ is the density of the medium and A is some characteristic area of the body; in this case the area is the product of length and diameter.

A set of orthogonal axes are chosen to define three coefficients C'_n, C_t and C_s (Fig. 1) appropriate to the normal, tangential and side forces. This terminology is used for compatibility with Ferro and Hou (1984) where C_n is taken as the coefficient related to the normal velocity component V sin α, so that $C'_n = C_n \sin^2 \alpha$. For a smooth cable, C_s is taken to be zero whereas a stranded cable creates round it a circulation due to the strands, producing a lift force and non-zero value of C_s.

Measurements have been made on two smooth cables of different weight per unit length and two stranded wires (three and six strands), approximately 200 m long, to determine their force coefficients over a range of speeds from 0.4 to 2.8 m s^{-1}. The range of Reynolds Numbers based on cable diameter is from 3×10^3 to 3×10^4.

Normal and tangential force coefficients have been computed for the smooth cables, and normal, tangential and side force coefficients for the stranded wires (see Fig. 1).

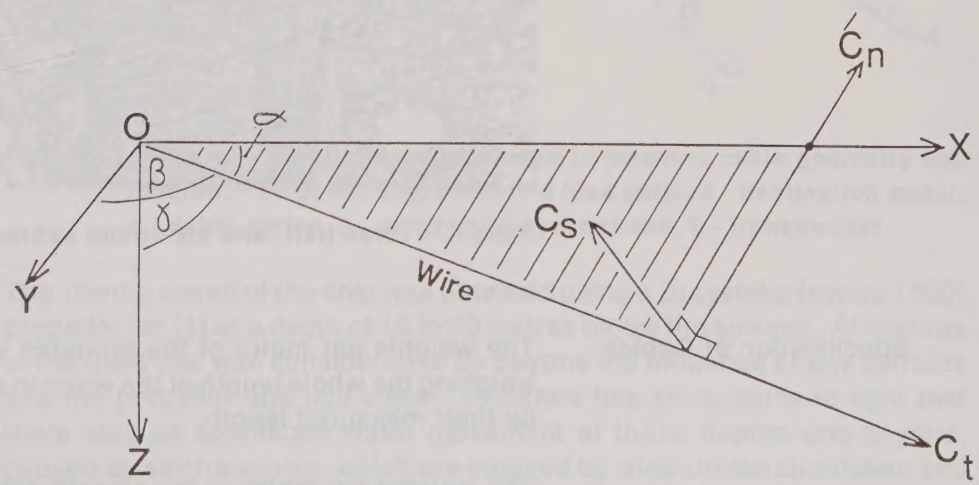

Figure 1. Definitions of normal (C'_n), tangential (C_t) and side (C_s) force coefficients of a wire having angles α, β and γ to the X, Y and Z axes. OX is the direction of water velocity, OY is perpendicular to OX and OZ, and OZ is vertically downwards.

The project was undertaken in collaboration with the British Hydromechanics Research Association (BHRA). The aim was to determine these coefficients under a variety of conditions for use by fishing gear technologists, particularly in calculating trawl gear performance. Given a minimum set of measurements such as the tension in the cable at one end, the depth differential and the horizontal transverse separation between the ends, it is possible, with accurate force coefficients, to calculate the complete shape of the cable and hence to resolve the cable loads. Detailed analysis of the major forces acting on the gear such as net drag and otter-board spreading forces is then possible. These results supplement those presented by Ferro and Hou (1984).

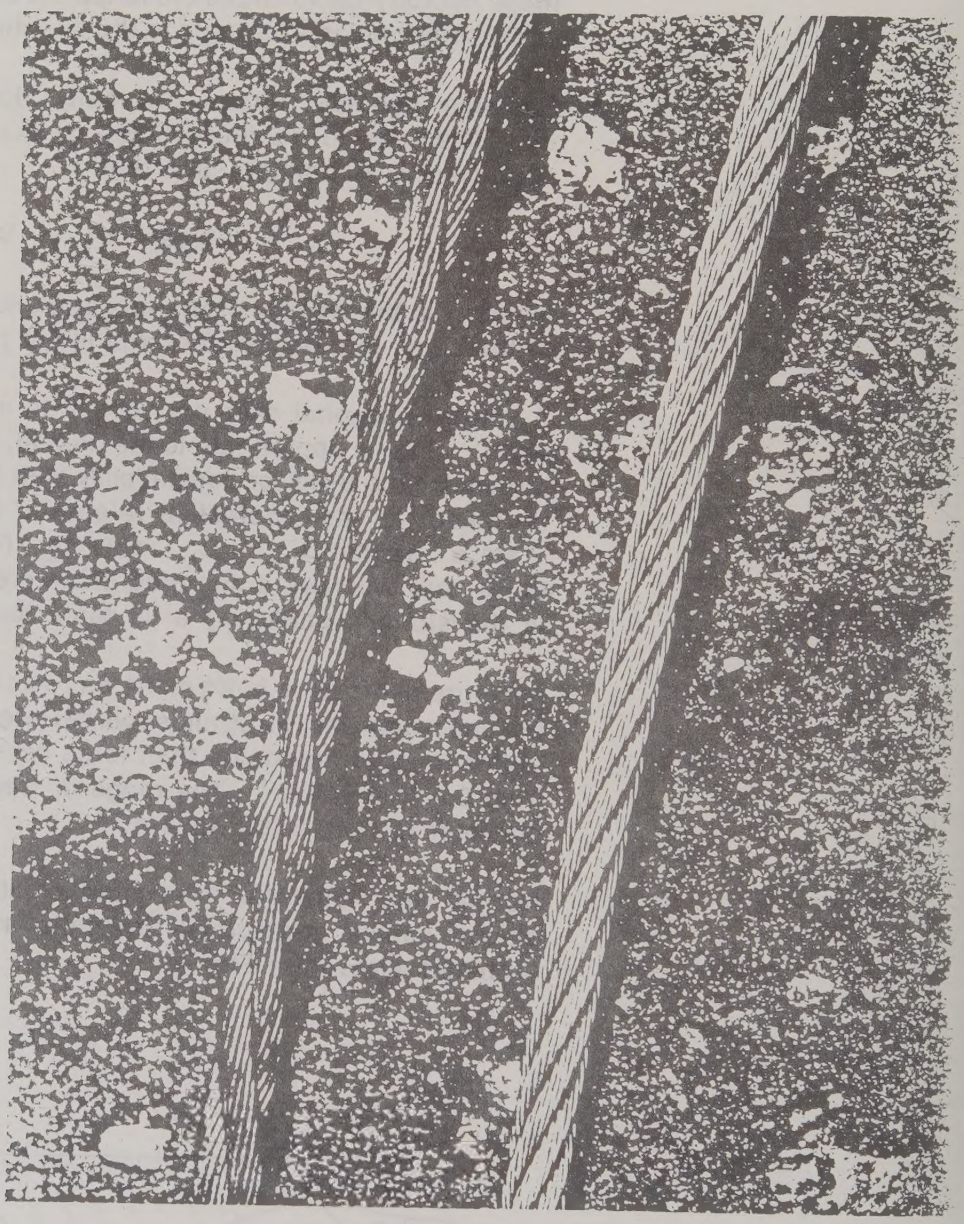

Plate I. Three (left) and six strand cables.

Specification of Cables

The weights per metre of the stranded wires (Table I) were obtained by weighing the whole length of the wires in air and in fresh water and dividing by their measured length.

The weights per metre of the smooth cables were obtained by weighing a precisely measured length of one metre in air. Their volume and hence weight per length in water were calculated using the measured diameter.

The diameters of the wires were measured at ten points spaced along their length. The standard errors of the means are quoted. For a stranded cable the diameter is taken as the mean diameter of the circumscribing cylinder.

The three strand cable was new and had been degreased so that the grooves between the strands were not blocked (Plate I). The six strand cable had been well used and the grooves were blocked with grease to some extent.

Trials Method

The experiments were conducted on board the 110 hp Fisheries Research Vessel "Goldseeker" in Loch Ness, a deep fresh-water loch. The cables were towed with no weights on their lower ends so that they were almost straight over their whole length and tension at the upper end reduced as speed increased initially.

The vessel steered a straight course at constant engine setting for five to fifteen minutes until an equilibrium state was reached and sufficient measurements had been taken. The wires were towed at several different speeds during each tow. Most instruments produced average values every 30 seconds. Several of these 30-second means were averaged to give a final reading representing each condition.

Instrumentation

The positions of the instruments are indicated in Figure 2.

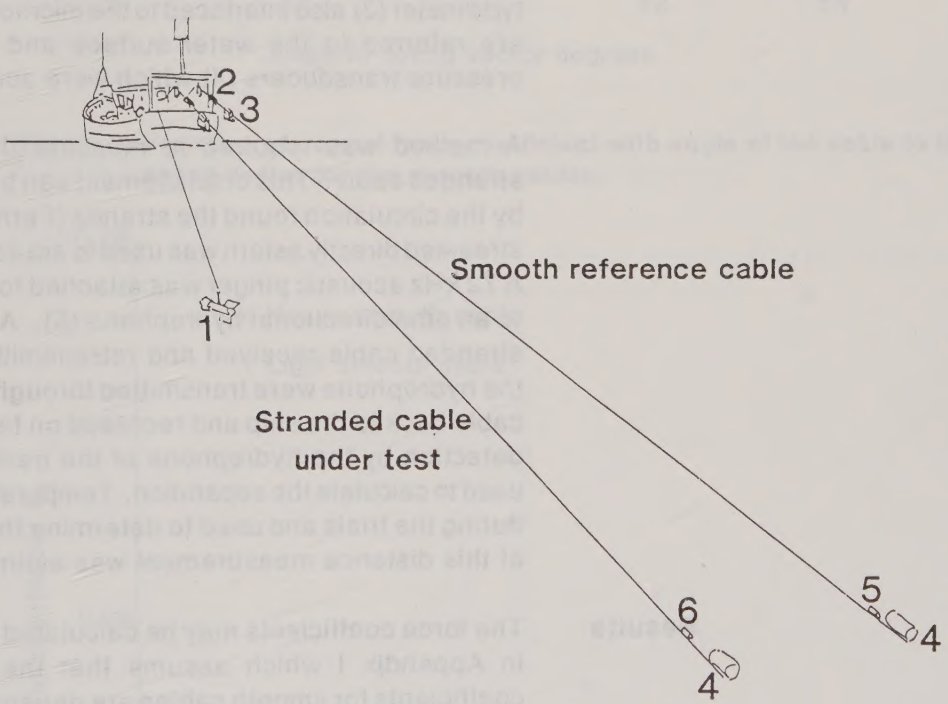

Figure 2. The positions of instruments used to measure cable geometry and loading. 1 - Speed log, 2 - in-line load cells, 3 - declination meter, 4 - depth meter, 5 - pinger and hydrophone, 6 - transponder.

The towing speed of the ship was obtained using a Braystoke (series 1000) propeller log (1) at a depth of 10 to 20 metres below the surface. At the time of the trials this was considered to be beyond the influence of any currents and the propeller and hull wake. Evidence has since come to light that there may be significant water movement at these depths and beyond, caused by seiche waves, which are induced by wind-driven circulation and can attain speeds of the order of 0.3 m s^{-1}. The log was calibrated against a Decca Trisponder distance measuring system. The accuracy of the propeller log itself was considered to be $\pm$ 0.01 m s^{-1}. The log failed during one haul and speeds were estimated from depth measurements using the variation of depth with speed obtained from three other similar hauls.

Table 1

Specification of wires and cables

Cable specification	Weight in air (kg m^{-1})	Weight in water (kg m^{-1})	Diameter with 95% confidence limits (mm)	Pitch per turn (mm)	Strand diameter (mm)
Light smooth	0.200	0.083	12.2 ± 0.0	–	–
Heavy smooth	0.648	0.400	17.8 ± 0.03	–	–
6 strand 6 x 19 (9 x 9 x 1) Z twist	0.379	0.297	10.4 ± 0.03	72	3.5
3 strand 3 x 19 (12 x 6 x 1) S twist	0.481	0.403	11.0 ± 0.08	80	5.6

Tension was measured at the towing point by 1,000 lb (454 kg) in-line strain gauge load cells (2) to ± 1 kg. The data were interfaced directly to an 8-bit microcomputer. Declination angle of the wire at the ship, ie the angle between the wire and the horizontal plane, was measured by a pendulum type meter (3) also interfaced to the microcomputer. The depth measurements are referred to the water surface and were obtained by self-recording pressure transducers (4) which were accurate to ± 0.7 m (Mitchell, 1981).

A method was required to measure the transverse displacement of a stranded cable. This displacement can be caused by the side force created by the circulation round the strands (Ferro and Hou, 1984). A smooth cable streamed directly astern was used to act as a reference for the measurements. A 72 kHz acoustic pinger was attached to the end of the smooth cable close to an omnidirectional hydrophone (5). A transponder (6) on the end of the stranded cable received and retransmitted the pulses. The signals from the hydrophone were transmitted through the conductors inside the smooth cable back to the ship and recorded on tape. The time interval between the detection by the hydrophone of the transmitted and the return pulse was used to calculate the separation. Temperature profiles were taken periodically during the trials and used to determine the velocity of sound. The accuracy of this distance measurement was estimated to be ± 0.6 m.

Results

The force coefficients may be calculated directly using the equations given in Appendix I which assume that the cable is straight. The normal coefficients for smooth cables are dependent on cable weight and diameter and measured speed and depth only. The coefficients for stranded cables are, in addition, slightly dependent on the transverse displacement from the reference cable (see section on instrumentation). The tangential coefficients are dependent on cable weight and diameter and measured speed, depth and tension. The side force coefficients for stranded cables are dependent on cable weight and diameter and measured speed, depth and transverse displacement from the reference cable.

Smooth Cables

The normal coefficients are scattered about a mean value of 2.02. There is no clear variation with angle to the speed vector (Fig. 3). The scatter is greater at lower speeds (higher angles).

The tangential coefficients (Fig. 4) show an increase with angle of attack up to about 30° in the case of the heavier cable from an initial value of between 0.01 to 0.02 when the cable is parallel to the flow. Above 30° there is more scatter.

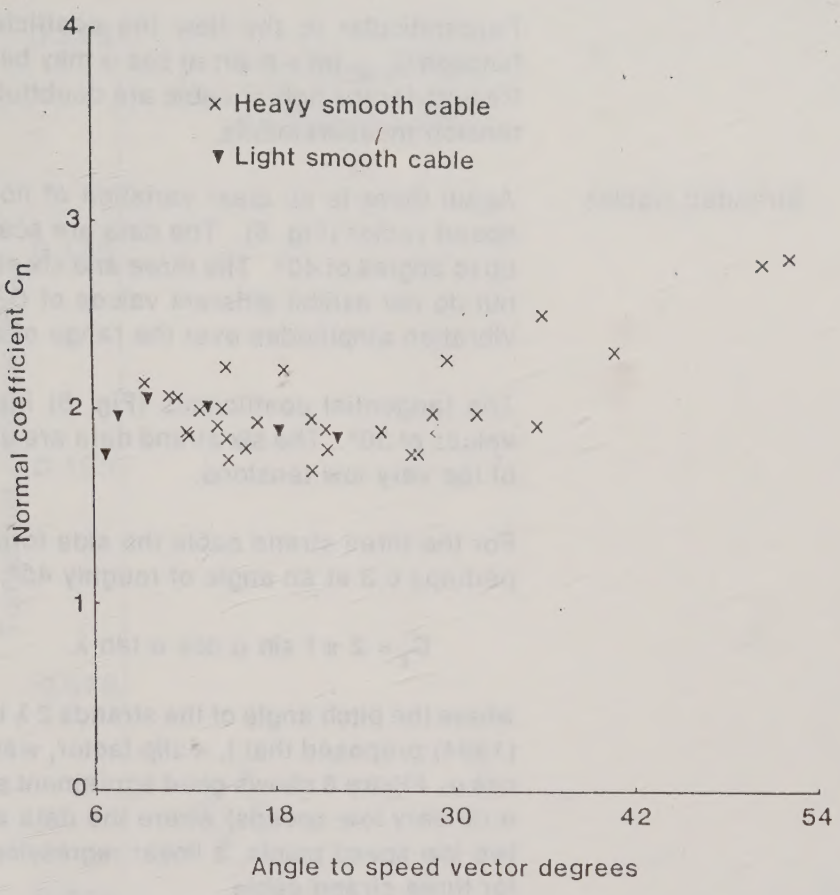

Figure 3. Variation of normal force coefficient with angle of the cable to the speed vector for two smooth cables.

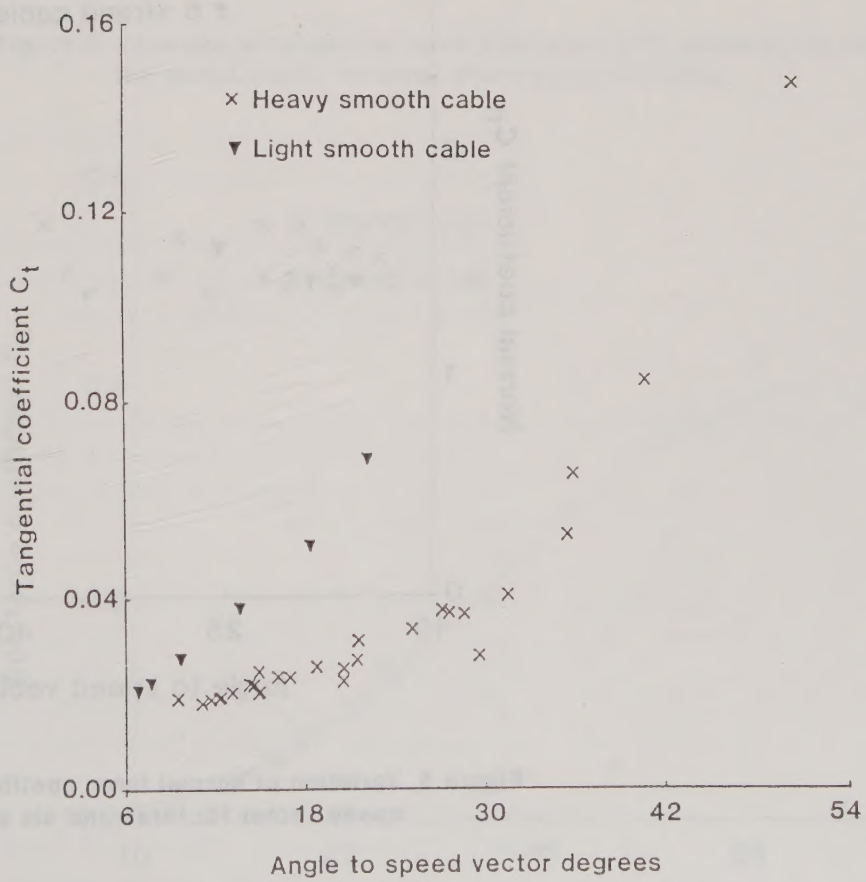

Figure 4. Variation of tangential force coefficient with angle of the cable to the speed vector for two smooth cables.

Perpendicular to the flow the coefficients should be zero so that the function $C_{n\,90}\,(m + n \sin \alpha) \cos \alpha$ may be applicable (Ferro and Hou, 1984). Results for the lighter cable are doubtful because of uncertainty in the low tension measurements.

Stranded Cables

Again there is no clear variation of normal coefficient with angle to the speed vector (Fig. 5). The data are scattered about a mean value of 1.47 up to angles of 40°. The three and six strand cables are of different weight but do not exhibit different values of C_n suggesting that they have similar vibration amplitudes over the range of speed.

The tangential coefficients (Fig. 6) increase with angle of attack up to values of 30°. The six strand data are unreliable at larger angles because of the very low tensions.

For the three strand cable the side force coefficients (Fig. 7) increase to perhaps 0.3 at an angle of roughly 45°. In the function

$$C_s' = 2\,\pi\,f \sin \alpha \cos \alpha \tan \lambda$$

where the pitch angle of the strands $2\,\lambda$ is 23.4° in this case, Ferro and Hou (1984) proposed that f, a slip factor, was a linear function of the square of $\cos \alpha$. Figure 8 shows good agreement except at very large values of angle α (ie very low speeds) where the data are not accurate. Excluding these two low speed points, a linear regression gives $f = (0.940 - 0.913 \cos^2 \alpha)$ for three strand cable.

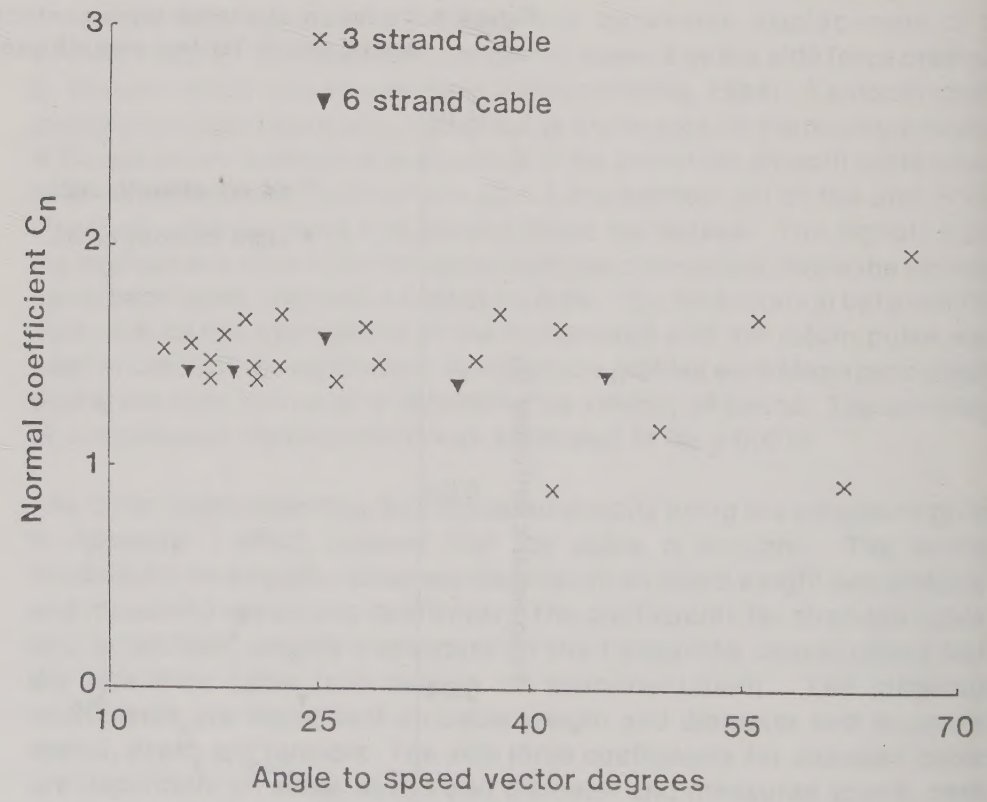

Figure 5. Variation of normal force coefficient with angle of the cable to the speed vector for three and six strand cables.

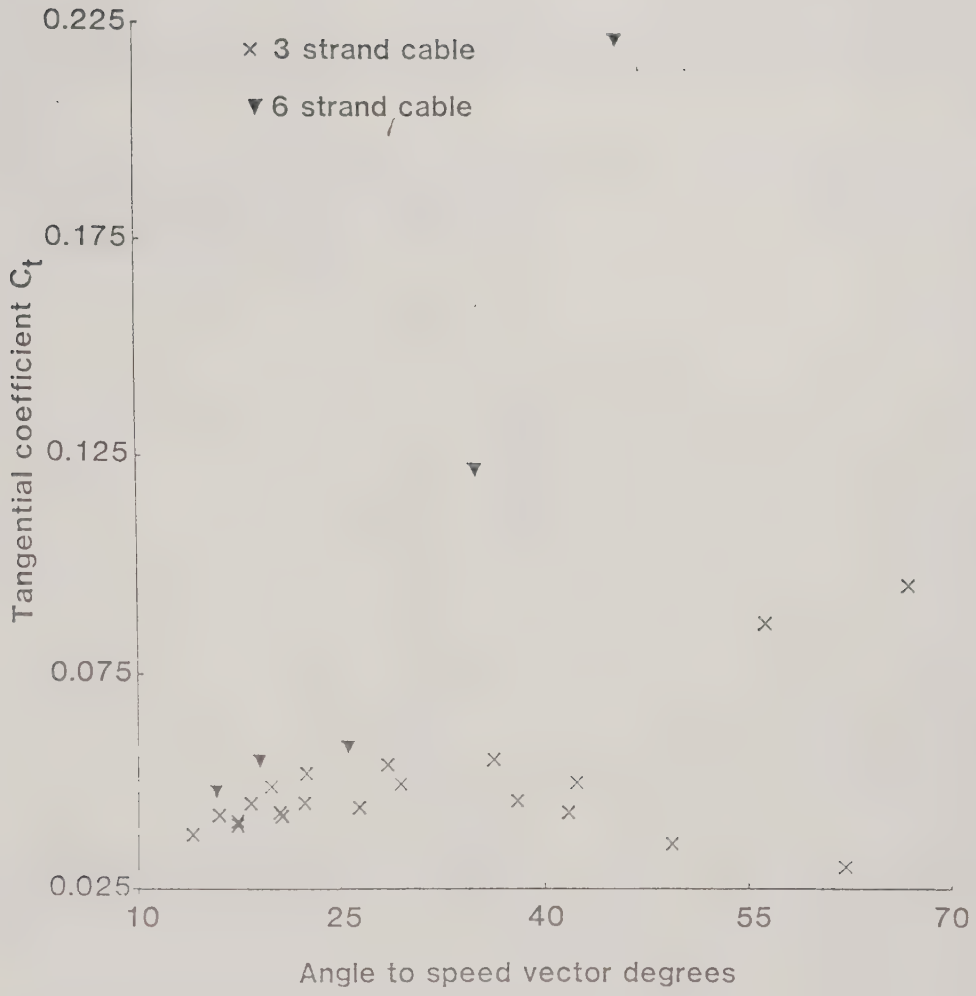

Figure 6. Variation of tangential force coefficient with angle of the cable to the speed vector for three and six strand cables.

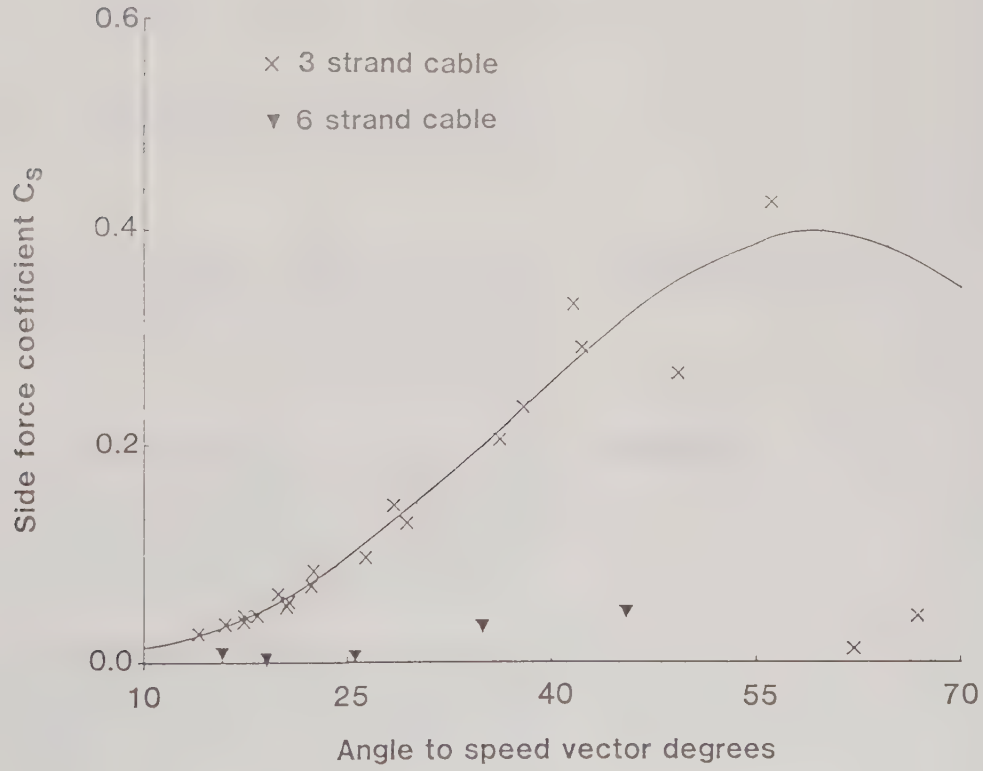

Figure 7. Variation of side force coefficient with angle of the cable to the speed vector for three and six strand cables.

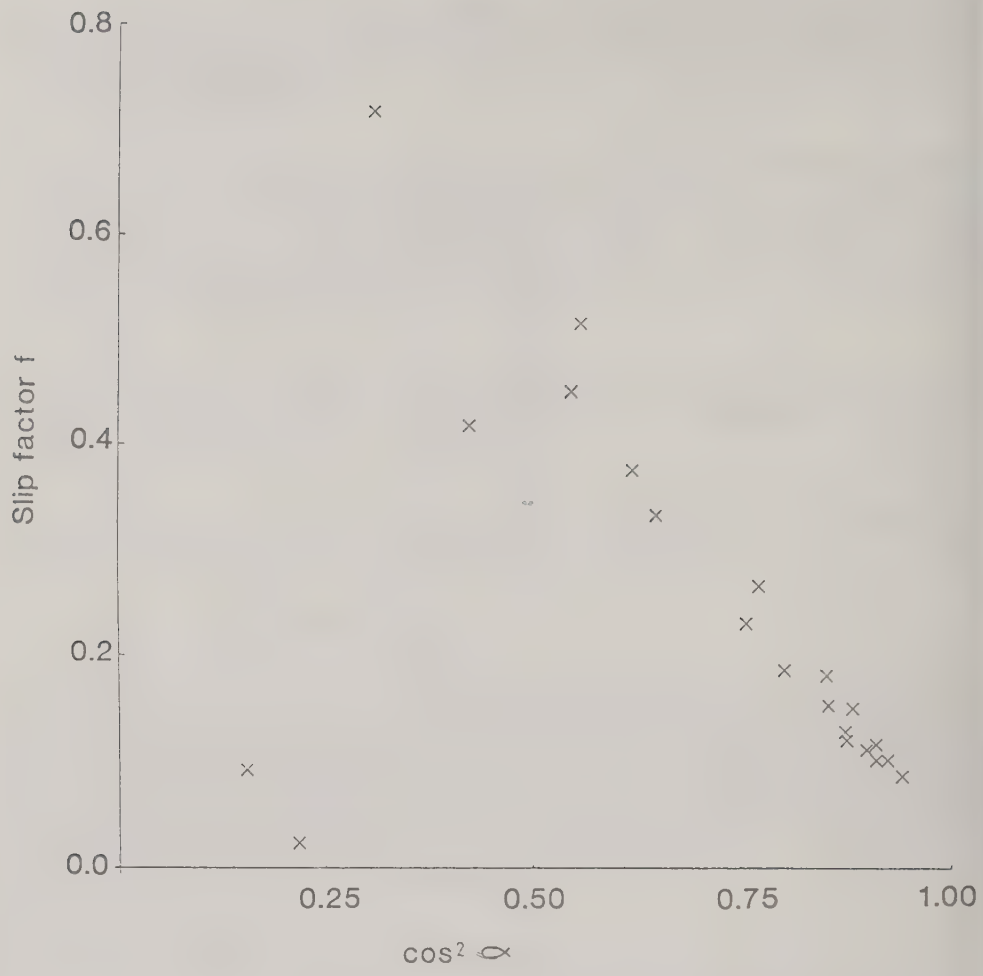

Figure 8. Variation of slip factor for three strand cables with $\cos^2 \alpha$ where α is the angle of the cable to the speed vector.

Using this expression for slip factor, the variation of C_s with angle α is shown as the solid line in Figure 7.

The six strand cable shows very low values of C_s. This may be explained by the state of the wire which was well worn and greased, as it would be in normal commercial fishing practice.

Acknowledgements

I am grateful for the collaboration of Malcolm Every of BHRA during these trials and for the help of many people including Amanda Huntridge, Don Urquhart, Bob Mitchell, Angus Macdonald and the skipper and crew of FRV "Goldseeker".

Summary

Measurements have been made on two smooth cables weighing 0.2 and 0.648 kg m^{-1} in air and on two stranded cables having three and six strand construction. The cables were approximately 200 m long and were towed with no weight attached to their lower ends at between 0.4 and 2.8 m s^{-1} corresponding to angles to the speed vector between 70° and 6° respectively.

Variations of the normal, tangential and side force coefficients with wire angle are presented. The normal force coefficients have mean values of 2.02 and 1.47 for the smooth and stranded cables respectively. The tangential force coefficients increase with angle to the velocity vector to values of the order of 0.1. The side force coefficient for the three strand cable increases to a value of 0.4 at an angle of about 60° before reducing again as the cable becomes normal to the flow.

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Appendix I

Calculation of force coefficients

A straight cable has diameter d, length l, weight per unit length W, tension T at its upper end, depth z of its lower end, and horizontal spread of its lower end perpendicular to the direction of motion y. Water density is ρ.

The definition of a force coefficient is

$$C_i = F_i / (\tfrac{1}{2} \rho V^2 l d)$$

where F_i is the hydrodynamic force component acting on the wire in the direction i and V is the relative velocity between the water and the wire.

(i) Stranded cable:

$$C_n = C'_n / \sin^2 \alpha = (W/k) (\cos \alpha \cos \gamma / \sin^3 \alpha)$$

$$C_t = (W/k) [(T/W/l) - \cos \gamma]$$

$$C_s = (W/k) (\cos \beta / \sin \alpha)$$

where $k = \tfrac{1}{2}\rho V^2 d$

$$\cos \gamma = z/l$$

$$\cos \beta = y/l$$

and $\cos^2 \alpha = 1 - \cos^2 \beta - \cos^2 \gamma$.

(ii) Smooth cable:

It is assumed to be in one plane so that $\cos \gamma = \sin \alpha$ and $\cos \beta = 0$ since $C_s = 0$

$$C_n = C'_n / \sin^2 \alpha = (W/k) (\cos \alpha / \sin^2 \alpha)$$

$$C_t = (W/k) [(T/W/l) - \sin \alpha]$$

$$C_s = 0.$$

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